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THE IMPACT CHARACTERISTICS OF A WATER DROPLET ON A FLAT PLATE IN TWO-PHASE, AIR-WATER SPRAY FLOW

THESIS

GAM/ME/67-7 Albert A. Gagliardi, Jr.
Capt. USAF

SCHOOL OF ENGINEERING

WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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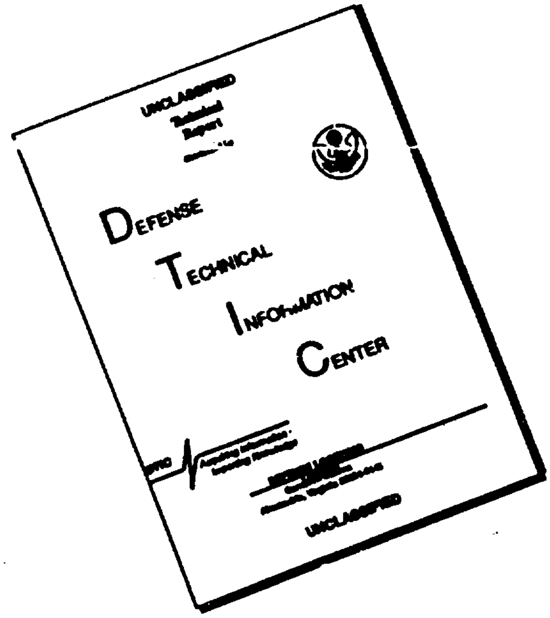

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AFLC-WPAFB-AUG 67 35

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THESIS

Presented to the Faculty of the School of Engineering

of the

Air Force Institute of Technology

Air University

in Partial Fulfillment of

the Requirements for

the Degree of Master of Science

by

Albert A. Gagliardi Jr., B.S.

Capt. USAF

Graduate Aerospace and Mechanical Engineering

May 1967

Preface

Previous studies of heat transfer in two-phase, air-water spray flow illustrate the complexity and the number of variables present in such a study. I have attempted to analyze only one variable, the water droplet's impact characteristic; and then, by the use of known heat transfer phenomena, tried to predict its effect on the heat transfer rate.

This study has been both interesting and challenging because, to my knowledge, no previous attempt has been made to study this particular segment of heat transfer.

There are many people who have earned my deepest respect and gratitude for their assistance in this endeavor. I would like to thank Dr. Max G. Scherberg of the Aerospace Research Laboratory and Dr. Harold E. Wright of the Air Force Institute of Technology who together have served as motivators and advisors. Mr. Clifford D. Howell of the Technical Photographic Branch, Aerospace Systems Division deserves a special acknowledgement, for without his photographic skill, all might have been in vain. Mr. William W. Baker of the Mechanical Engineering Laboratory was especially helpful when I needed assistance in the construction and installation of equipment.

Albert A. Gagliardi, Jr.

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List of Symbols

B	Bounce Characteristic
B-S	Bounce-Splash Characteristic
C_p	Pressure Coefficient
d	Droplet Diameter
g_c	Gravitational Constant
mv	Droplet Momentum
P_s	Static Pressure
P_t	Total Pressure
r	Plate Radius
S	Splash Characteristic
t	Time
V	Air Velocity
V_d	Droplet Velocity
ρ	Density
μ	Microns

Abstract

The purpose of this study was twofold; to determine experimentally the impact characteristics of a water droplet impinging on a flat plate in two-phase, air-water spray flow, and to predict on the basis of known heat transfer phenomena, the effect of the impact characteristic on heat transfer.

The apparatus used consisted of a vertical wind tunnel, spray nozzle, spray nozzle adaptor, flat plate, and pressure measuring equipment. High speed motion picture photography was employed to record the impact characteristics as well as to determine the size and velocity of each droplet.

It was observed that a droplet exhibits either one of three impact characteristics: bounce, bounce-splash, and splash. The particular impact characteristic of a droplet was found to be primarily dependent upon its momentum. A discussion of the predicted effect of the impact characteristics on heat transfer is included in the report. The analysis indicates that heat transfer rates are augmented by all of the observed impact characteristics, and that higher values of heat transfer may be expected with increasing droplet momentum.

THE IMPACT CHARACTERISTICS OF A WATER DROPLET ON A FLAT PLATE IN TWO-PHASE, AIR-WATER SPRAY FLOW

I. Introduction

Background

Previous studies of heat transfer in two-phase, air-water spray flow have all indicated that higher heat transfer rates are obtained from a solid surface when a secondary phase in droplet form is added to the cooling airstream (1, 2, 5, 6, 7).* These studies were conducted at various water to air mass flow ratios between 0 and 0.1. The overall heat transfer process is dependent upon many variables, and to date the development of a simple analytical model has not been possible. Some of the variables encountered in two-phase flow are as follows:

1. The airstream velocity
2. Droplet size
3. Droplet velocity
4. The absolute mass of water impinging on the heat transfer surface
5. The water droplet's impact characteristic

The Marquardt Corporation (2) and Northern Research Corporation (6) have both reported that heat transfer in the region of the stagnation point is further augmented when water droplets are observed to bounce and erupt from the liquid film upon impact.

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*Numbers in parentheses refer to references in the Bibliography

Purpose

This study has a twofold purpose: first, to determine experimentally the impact characteristics of a water droplet impinging on the liquid film formed on the surface of a flat plate mounted normal to the flow, and secondly, to predict on the basis of known heat transfer phenomena, the effect of the impact characteristics on heat transfer.

Scope

Only the impact characteristics of a water droplet impinging on a liquid film are presented in this report. References 8 and 3 describe the collision of a water droplet with a solid surface in the absence of a liquid film for both a heated and unheated surface respectively.

Since this study was conducted with an unheated plate, the heat transfer predictions are based only on the observed impact characteristics and the information contained in the literature. The results apply to heat transfer applications where the surface temperature is below that at which flash evaporization of the water droplet would occur on impact. If the surface temperature is sufficiently high, a layer of vapor forms between the surface of the plate and the liquid film. Once this vapor layer is formed, further increases in surface temperature have little effect on the heat transfer. Gaugler (4) has analysed this particular segment of heat transfer, and although the initial conditions are quite different, the heat transfer conclusions are remarkably similar.

II. Description of Apparatus

The equipment used in this study consisted of a wind tunnel, spray nozzle, spray nozzle adaptor, flat plate, and a high speed motion picture camera. Sufficient instrumentation was employed to determine the pressure distribution of the plate as well as the size and velocity of the observed water droplets. A schematic diagram of the test apparatus is presented in Figure 1.

Wind Tunnel

A vertical wind tunnel with a 10 by 10 inch horizontal test section and velocity variations from 40 to 160 feet per second was used. Room air was drawn in through a 30 by 30 inch intake area and exhausted through a ducting system to the atmosphere. A complete description of the wind tunnel can be found in Reference 1.

Spray Nozzle

In order to determine the impact characteristics, some degree of control of the droplet size was essential. A spray nozzle gives a bell-curve distribution of droplet sizes and individual droplets can be isolated and studied. Also, by using a liquid-air nozzle, the median droplet size can be varied by altering the ratio of the nozzle air pressure to the nozzle water pressure. For these reasons a Spraying Systems Company type 1/4 J, liquid-air nozzle was selected.

Spray Nozzle Adaptor

When the entire spray of the nozzle enters the wind tunnel test section, a large number of droplets impinge upon the liquid film, and one droplet cannot be isolated and studied. Therefore, at the suggestion of Dr. Max Scherberg, a nozzle adaptor was designed and contructed so that only a portion of the spray is allowed to enter the wind tunnel test section. The nozzle adaptor has a hollow cone in its base with a 1/8 inch hole drilled in the apex. As the spray strikes the cone, only that portion passing through the hole enters the wind tunnel. A schematic diagram of both the spray nozzle and spray nozzle adaptor is shown in Figure 2. Two other devices were tested to isolate a water droplet and are discussed in Appendix D.

Flat Plate

Since little is known about the variables governing the heat transfer rate in the region of the stagnation point, a flat plate was chosen as the test model (Fig 3). The flat plate has the advantage of a large stagnation region and is easy to construct. Pressure taps were located symmetrically in the surface of the plate in order to measure the pressure distribution. The taps also served as a means to inject water and dye onto the plate.

High Speed Motion Picture Camera

A Wollensak Fastax camera with associated electronic timing equipment was employed to photograph the droplets impinging on the liquid film. The camera had a film speed capability of 7000 frames per second and sufficient magnification to photograph droplets with diameters in the range of 100 microns.

III. Experimental Procedure

Pressure Distribution

A single-phase pressure distribution of the plate was measured at four air velocities: 50, 90, 120, and 145 feet per second. For each velocity, three runs were made. The plate remained normal to the flow but was rotated 120 degrees between runs. For all runs, a reversed curvature was obtained in the pressure profile. A curve has been fitted to the data points (averaged value of the three runs) in order to compare the profile to the experimental one obtained by Albrecht (1). Reference 9 describes the formation of radial vortices emenating from the stagnation point in incompressible flow. If a radial vortex sheet were present on the flat plate, this could create a dissipation of pressure near the center and account for the reversed curvature obtained. The results of the pressure distribution determination are shown in Figure 4.

Droplet Studies

In order to have a complete set of data, a static test was conducted to observe the droplet impact characteristics at low velocities. The plate was mounted on a test stand and the nozzle was located 40 inches above it to duplicate the mounting in the wind tunnel. To keep the number of droplets impinging on the liquid film to a minimum, a nozzle adaptor was used. A nozzle water and air pressure of 10 in Hg and 20 in Hg, respectively, were found to yield the most uniform spray. These settings were maintained throughout the experimental portion of the study.

High speed motion pictures, both colored and black-and-white, were taken of the flow field. To photograph droplets with a diameter in the range of 100 microns, it was necessary to focus on an area approximately 2mm by 2mm with a focal plane depth of approximately 0.25mm. Most of the film was taken in the region of the stagnation point with the remainder being taken at the edge of the plate.

The photographic procedures developed in the static test were also used in the wind tunnel. Tests were conducted at three airstream velocities: 52, 82, and 125 feet per second. Within the wind tunnel, the nozzle adaptor did not provide a sufficient spray to maintain a uniform liquid film on the surface of the plate. For this reason, water was injected through the pressure taps onto the plate. One test was carried out on an elliptical cylinder to observe the impact characteristic of a droplet striking the liquid film at an incident angle of approximately 15 degrees. The incident angle is defined as the angle between the droplet's trajectory and the surface of the liquid film.

Summary of Droplet Studies

The impact characteristics of a water droplet impinging on a liquid film were determined by a series of photographic tests. Appendix A outlines the procedures followed to determine the size, velocity, and momentum of a water droplet. The momentum was used to categorize the impact characteristics observed, and the results are given in Section IV.

Since various focal distances and film speeds were used, the reader should not attempt to compare droplet sizes and velocities (droplet elongation) between the photographs shown in Appendix B. The measured values of size, velocity, and momentum of the droplet are contained in the figure titles.

IV. Results

Three impact characteristics were observed. The impact characteristics may be called droplet bounce, bounce-splash, and splash. Definitions of these characteristics will follow. It was found that the impact characteristic which a droplet will exhibit is primarily dependent upon its momentum. Therefore, the droplets have been categorized, on the basis of momentum, into the three regimes shown in Figure 5.

Bounce Regime

When the droplet arrives at the liquid film with a normal component of momentum below approximately $3.7 \times 10^{-9} lb_f$-sec, the droplet is not capable of overcoming the relatively high surface tension of the liquid film. In this case, the droplet rebounds from the surface as if it were an elastic sphere (Fig 6). In the stagnation region, droplets were observed to bounce a number of times until they were either swept away by the airstream or gradually absorbed into the liquid film. In the test on the elliptical cylinder, it appeared that a droplet impinging on the liquid film at an angle of approximately 15 degrees skipped from the surface and was swept downstream by the airflow.

Bounce-Splash Regime

It was observed that when the normal component of momentum is between approximately 3.7×10^{-9} and $6.0 \times 10^{-9} lb_f$-sec, the droplet may exhibit either of the three characteristics. The bounce-splash phenomena, although only observed in a few instances, occurs when the value of

droplet momentum is sufficient to rupture the surface of the liquid film. However, the droplet remains intact and rebounds from the surface (Fig 7). It appears that a small amount of the liquid film is splashed from the plate. The impact characteristics within this regime are unpredictable, and seem to depend on the local conditions of the liquid film at the instant of impact. Since the regime is ill-defined, the limits given are only approximate.

<u>Splash Regime</u>

If the normal component of droplet momentum exceeds approximately 6×10^{-9} lb_f-sec, the droplet not only has sufficient momentum to overcome the surface tension of the liquid film, but the surface tension of the droplet is also overcome (Fig 8). As the droplet impinges on the surface, a splash is created and the mass of water transported from the liquid film increases with increasing droplet momentum. This is shown in Figure 9. The splash creates many well defined droplets, some of which were observed to fall back to the surface and exhibit the bounce characteristic. If the momentum of the original droplet is sufficiently high, a percentage of the splashed droplets move far enough away from the plate to again be accelerated into the splash regime, and secondary splashes were observed. Although the mass of water transported from the liquid film increases with increased droplet momentum, the mass within the liquid film appears to remain constant. This is a result of the original droplet replacing liquid that is splashed away and secondary droplets returning to the liquid film and being absorbed.

V. Discussion and Interpretation

Discussion and Interpretation of Results

The impact characteristic which a droplet will exhibit is primarily dependent upon its component of momentum normal to the liquid film. As droplet momentum increases, the disturbances created within the liquid film become more pronounced. The disturbances range from a slight dimpling of the film in the case of a bouncing droplet, to relatively large disruptions from one in the splash regime. As a result of the droplets bouncing and splashing from the liquid film, a "halo" effect above the plate is created. When the spray nozzle and the wind tunnel are adjusted to yield higher values of droplet momentum, the "halo" becomes more clearly defined. This appears to be the phenomena observed by previous researchers in this field. Two photographs of the "halo" effect are shown in Figure 10.

The interaction between the liquid film and the droplet was observed by the use of colored photography. By injecting dye (Safranin Bluish) through the pressure taps, it was possible to color the liquid film red. The water droplet photographed white. Since a bouncing droplet remained white throughout its entire trajectory, this verified that no transfer of mass occured from the liquid film to the droplet. In the case of the bounce-splash droplet, the splash that seemed to occur appeared red. When the droplet rebounded, it was tinted red. However, this appears to be a thin coating of resident water (which is dyed red) rather than an exchange of mass between the droplet and the liquid film.

When a droplet in the splash regime impinged upon the liquid film, the droplets created were a deeper red indicating that this was primarily water which was resident in the liquid film.

The Predicted Effect of the Droplet's Impact Characteristic on Heat Transfer

For all of the impact characteristics observed, an augmentation in the heat transfer rate from a heated plate may be expected.

In the case of the bouncing droplet, additional heat transfer is predicted as a result of two mechanisms:

1. Conduction - The droplet is in contact with the liquid film for a finite period of time (approximately 2 msec) and a transfer of thermal energy will occur.
2. The liquid film is disturbed by the droplet's impact.

For a bounce-splash droplet, an increased augmentation is expected for the following reasons:

1. Conduction - The contact time (approximately 10 msec) between the droplet and the liquid film as well as the temperature encountered are increased. This is a result of the droplet penetrating the liquid film, possibly to the surface of the plate where the temperature is a maximum, prior to rebound.
2. Mass Transport - A small amount of the liquid film appears to be splashed from the plate with a resultant transfer of thermal energy.
3. The liquid film is disturbed by the droplet's penetration.

In the case of the splashing droplet, the additional heat transfer predicted may be quite significant. Increased augmentation should occur with increasing droplet momentum. Two mechanisms are important:

1. Mass Transfer - As the droplet impinges on the film, it is observed to break up and replace a portion of the liquid film that is displaced.

2. Turbulent Mixing - The mass transfer results in a mixing process in which the cooler liquid of the droplet is dispersed throughout the liquid film. A possibility exists that a portion of the cooling fluid may even reach the surface of the plate where the temperature is a maximum.

Based on the preceding heat transfer analysis, it appears that operation in the splash regime is most advantageous, and that for increasing droplet momentum, higher heat transfer rates may be expected. Also, within the stagnation region, the highest values of heat transfer should exist due to secondary bounces and splashes.

This entire discussion has been based on an individual droplet basis. In the normal two-phase cooling process, a large number of droplets are impinging on the liquid film, and other factors must be considered. Maintaining the mass flow of water and the airstream velocity constant, it is anticipated that an optimum droplet size exists for which the heat transfer rate is a maximum. For spray patterns with a median droplet size below optimum, the concentration of droplets is so high that interference between the oncoming droplets and those bouncing and splashing from the liquid film is possible. Also, the smaller droplets do not have sufficient momentum to cross the streamlines of flow and arrive at the heat transfer surface. The net result is that the mass of water impinging on the surface is reduced. This factor coupled with the low momentum of the droplets reaching the surface should result in a lower heat transfer rate. For droplets larger than optimum, an augmentation in heat

transfer per droplet is expected, however, the overall heat transfer rate should decrease as a result of the low values of droplet concentration.

VI. Conclusions

The impact characteristic which a droplet may exhibit is primarily dependent upon its component of momentum normal to the liquid film. Three impact characteristics were observed:

Bounce,	$0 < mv < 3.7 \times 10^{-9} lb_f\text{-sec}$
Bounce-Splash,	$3.7 \times 10^{-9} lb_f\text{-sec} < mv < 6.0 \times 10^{-9} lb_f\text{-sec}$
Splash,	$mv > 6.0 \times 10^{-9} lb_f\text{-sec}$

An augmentation in the heat transfer rate from a heated plate is expected for all of the observed impact characteristics. Operation in the splash regime appears to be most advantageous and higher values of heat transfer per droplet may be expected with increasing droplet momentum.

VII. Recommendations

Since a number of heat transfer predictions are contained within this report, an experimental program should be undertaken to verify their validity. Three particular studies would be especially helpful:

1. An experimental study to determine the effect of droplet momentum on the heat transfer rate from a liquid film. The droplet size should be maintained constant, and the momentum made variable through variations in droplet velocity.
2. An experimental study to determine if an optimum droplet size exists for which the heat transfer is a maximum in a two-phase flow.
3. An experimental study to determine if any correlation exists between the measured values of heat transfer and the variation in intensity of the "halo" effect.

Bibliography

1. Albrecht, J. R. An Experimental Investigation of the Heat Transfer Near the Stagnation Point in a Two-Phase, Air-Water Spray Flow. AFIT Thesis, 1967.

2. Acrivos, A., Ahern, J. E., and Nagy, A. R. "Research Investigation of Two-Component Heat Transfer," The Marquardt Corporation. ARL 64-1161. Wright-Patterson AFB, 1964.

3. Engel, O. G. "Waterdrop Collisions With Solid Surfaces," Journal of Research of the Natural Bureau of Standards, 54: 281-298 (May 1955).

4. Gaugler, R. E. Experimental Investigation of Spray Cooling of High Temperature Surfaces. Carnegie Institute of Technology, Ph.D Thesis, 1966.

5. Hoelscher, J. F. Study of Heat Transfer From a Heated Cylinder in Two-Phase, Water-Air Flow. AFIT Thesis, 1965.

6. Smith, J. E., et al. "Heat Transfer Studies of Water Spray Flows," Northern Research Corporation. ARL AF 33(615)-2340. Wright-Patterson AFB, 1966.

7. Takahara, E. W. Experimental Study of Heat Transfer From a Heated Circular Cylinder in Two-Phase, Water-Air Flow. AFIT Thesis, 1966.

8. Wachters, L. H. J. and Westerling, N. A. J. "The Heat Transfer From a Hot Wall to Impinging Water Drops in the Spheroidal State," Chemical Engineering Science, 21: 1047-1056 (1966).

9. Weiss, R. F. "Stability of the Stagnation Region to Three-Dimensional Disturbances," AVCO-Everett Research Laboratory AF 30(602) 2083, 2393, 2968. Everett, Mass., 1965.

Appendix A

Determination of the Size, Velocity, and Momentum of a Water Droplet

Appendix A

Determination of the Size, Velocity, and Momentum of a Water Droplet

A Wollensak Fastax camera with a film speed capability of 7000 frames per second was used to determine the size and velocity of the water droplets. A millimeter scale mounted on glass by means of an emulsion served as the reference to measure droplet size and velocity. The scale was oriented normal to the plate and photographed at the same focal distance used in the droplet studies. After photographing the scale, with the Fastax camera, it was removed from the plate. Whenever the focal distance was changed during the droplet studies, the procedure was repeated. By superimposing the photographs of the droplet studies and the photographs of the millimeter scale, the droplet size and velocity could be obtained.

The droplet size was determined by comparing the droplet width to the millimeter scale. The droplet velocity and momentum were obtained by use of the following formulas:

$$V_d \text{ (ft/sec)} = \frac{\text{distance (mm) x film speed (frames/sec)}}{\text{Number of frames x 305 (mm/ft)}}$$

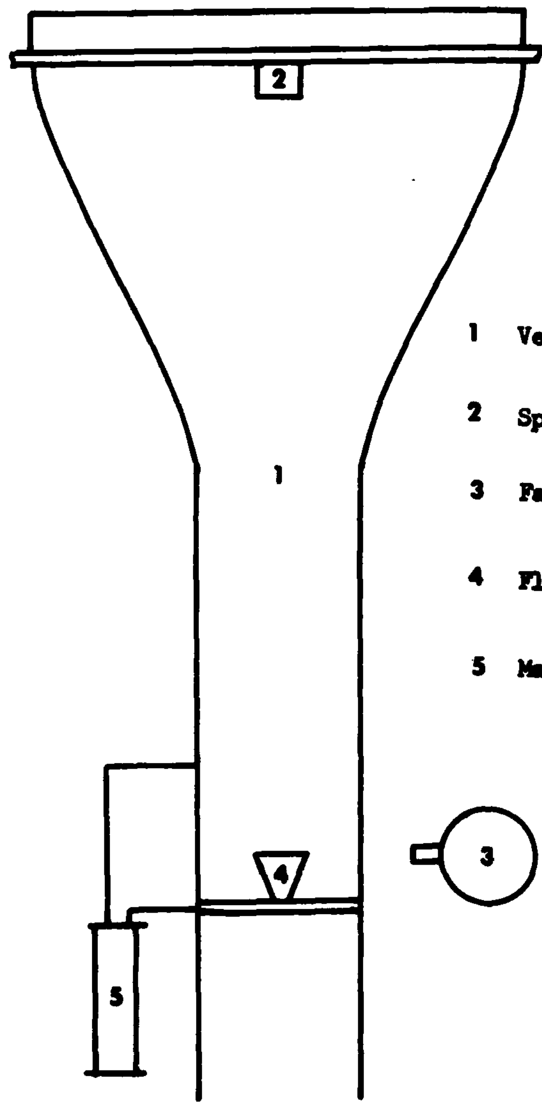
$$mv = \frac{\rho \pi d^3 V_d}{6 g_c}$$

Representative results of the determination of the size, velocity, and momentum as well as the impact characteristic of the water droplets are

shown in Tables I, II, III, and IV. Figures 11 and 12 are histograms plotted for one wind tunnel test to illustrate the distribution of droplet sizes and velocities obtained. Since the droplets were generally well-defined, the measured diameters should be a close approximation to the actual droplet size. The median droplet size indicated by the histogram should be larger than actual. This is a result of the inability to photograph droplets with a diameter less than approximately 125 microns. The elongation of the droplets is a result of the insufficient film speed obtained during the first portion of a roll of photographic film. Approximately three quarters of a 100 foot roll of film is used before the Fastax camera accelerates to the preset film speed

Appendix B

Figures



1 Vertical Wind Tunnel

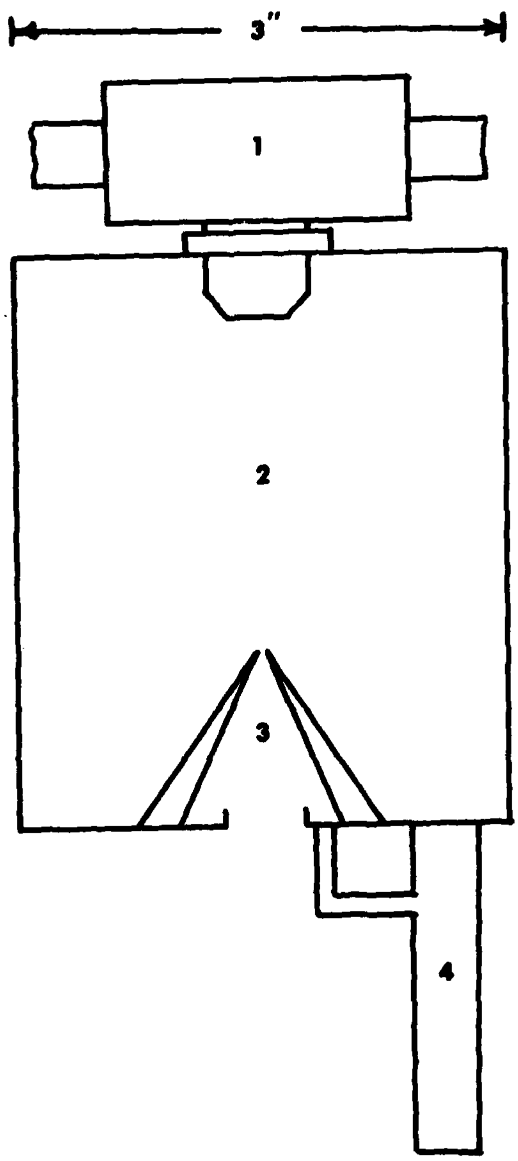
2 Spray Nozzle and Adaptor

3 Fastax Camera

4 Flat Plate

5 Manometer

Fig 1 Schematic of Test Apparatus



1 Spray Nozzle

2 Spray Nozzle Adaptor

3 Hollow Cone

4 Drain

Fig 2 Schematic of Spray Nozzle and Spray Nozzle Adaptor

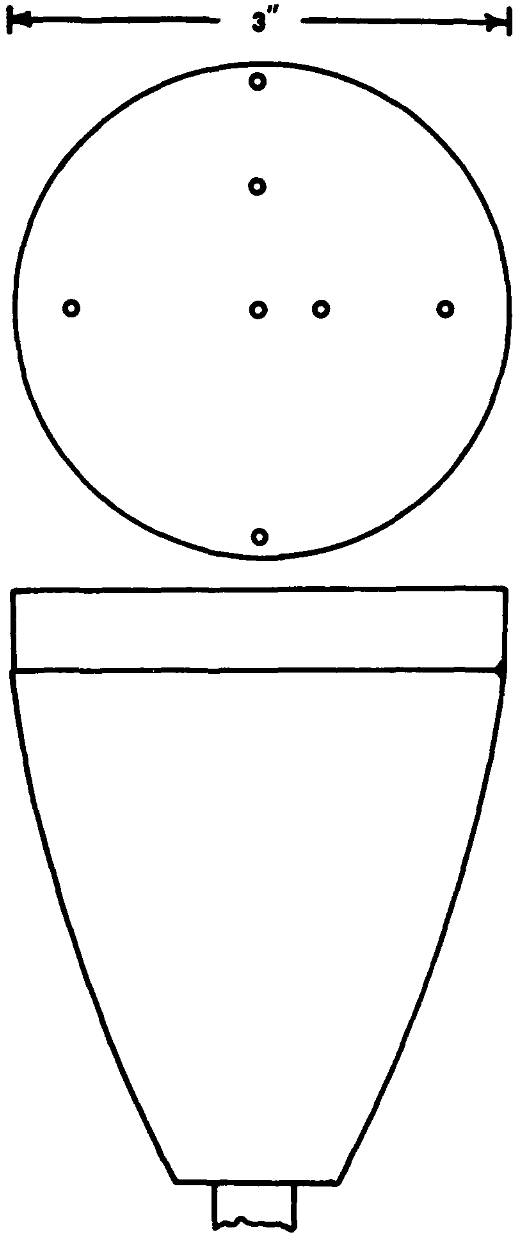


Fig 3 Schematic of Flat Plate

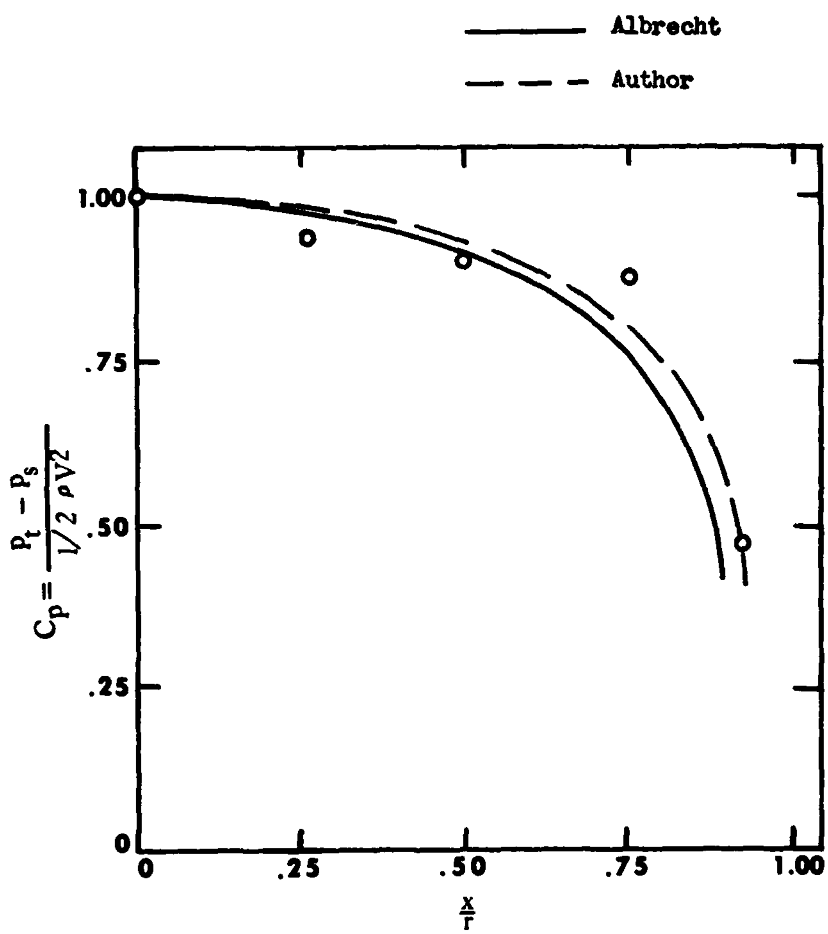


Fig 4 Pressure Profile of the Flat Plate

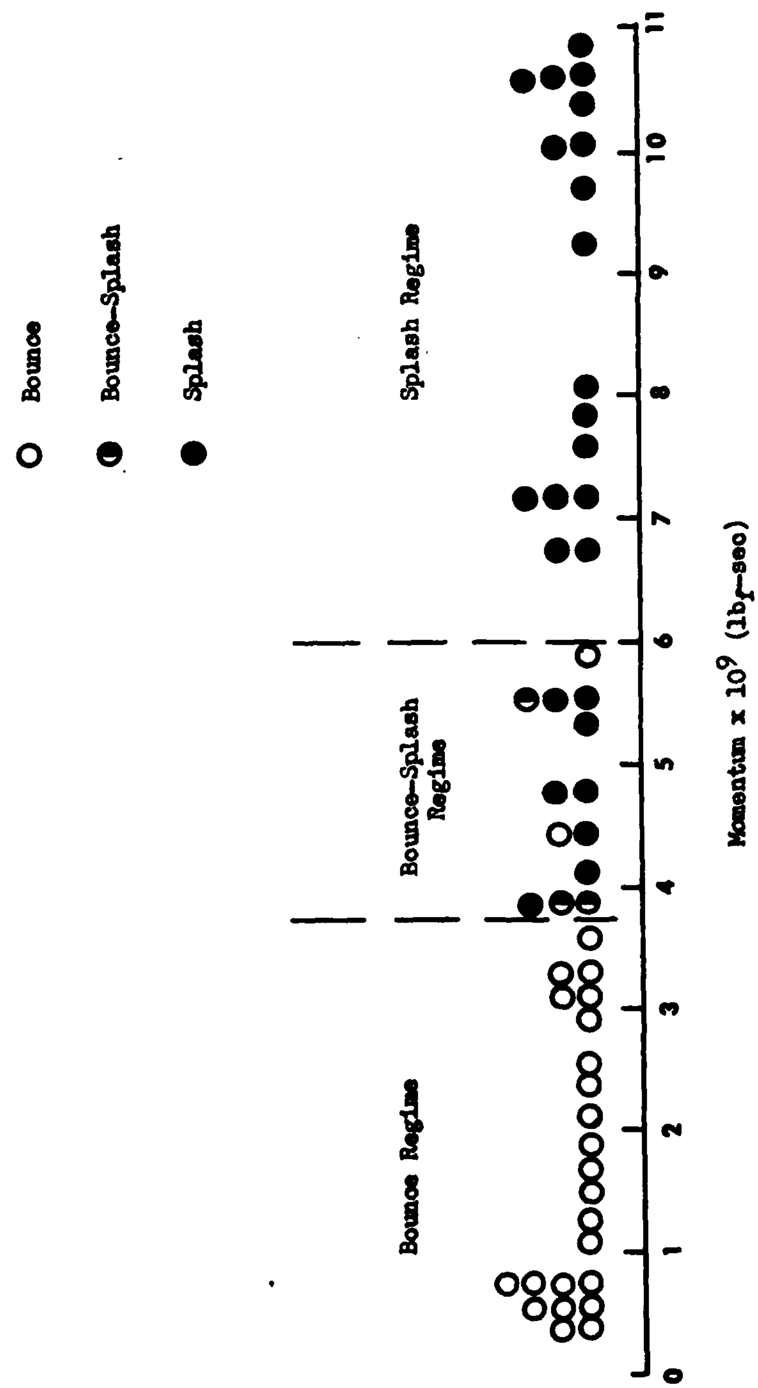
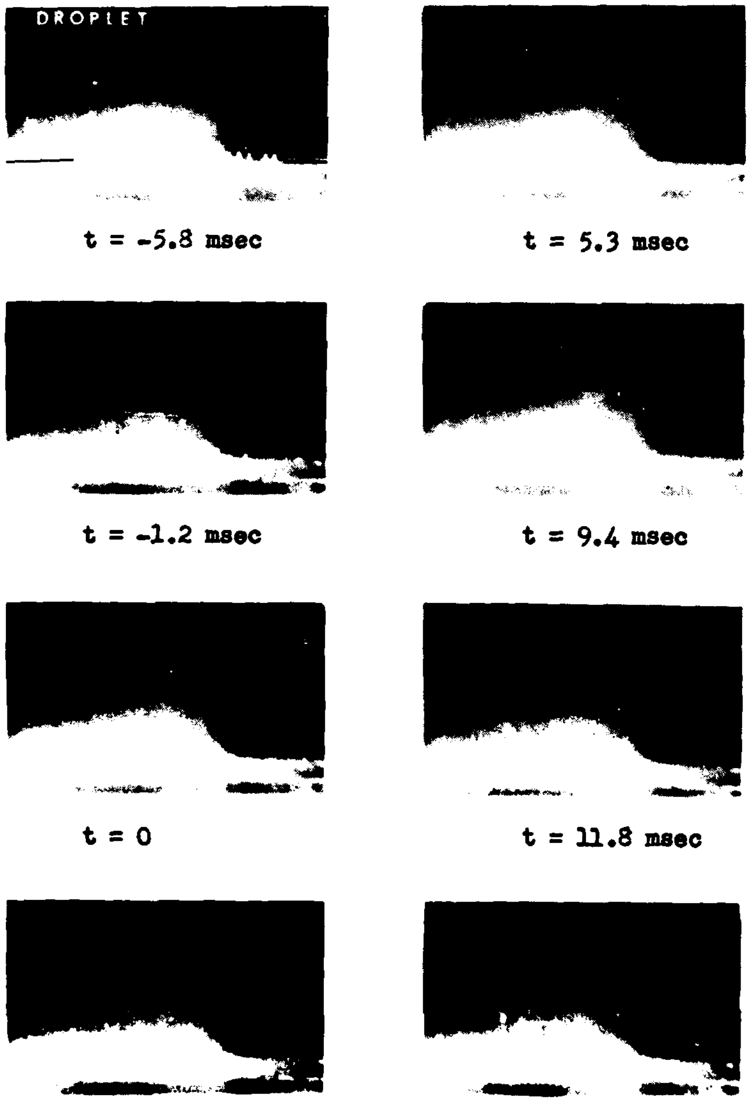


Fig 5 Regimes of Droplet Impact Characteristics



t = -5.8 msec

t = 5.3 msec

t = -1.2 msec

t = 9.4 msec

t = 0

t = 11.8 msec

t = 2.4 msec

t = 15.9 msec

Fig 6 Droplet Bounce Characteristic: $d = 250\,\mu$, $V_d = 5.34$ ft/sec, $mv = 2.98 \times 10^{-9}$ lb_f-sec

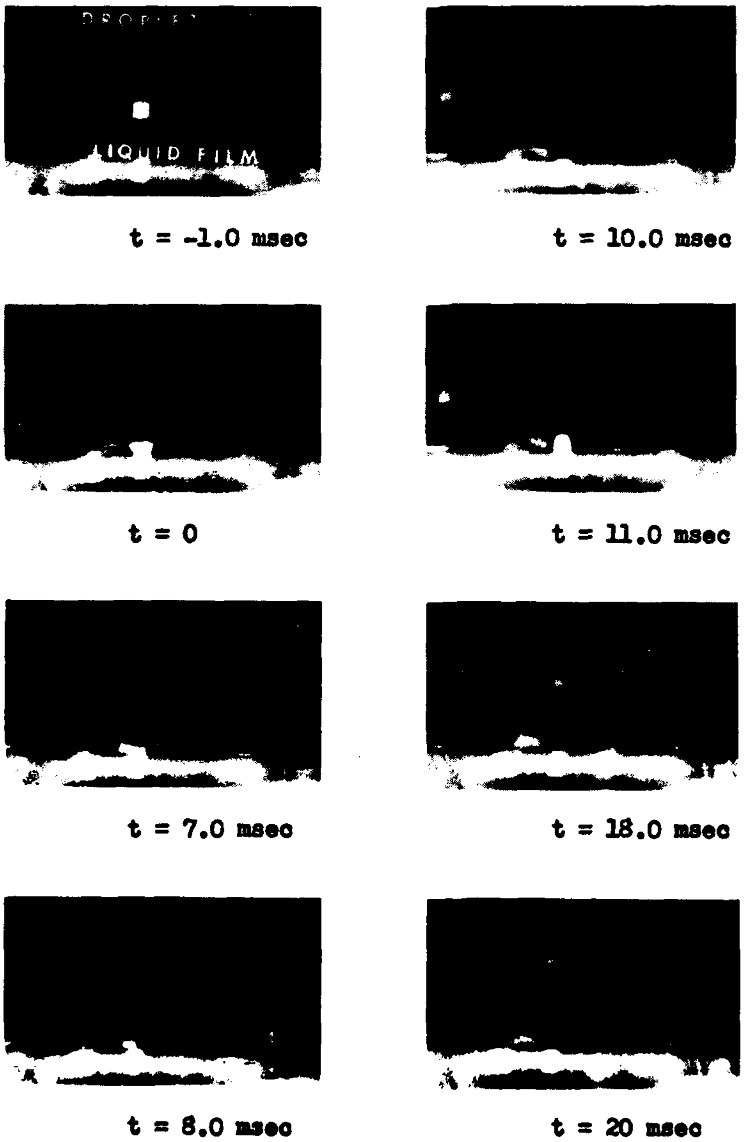


Fig 7 Droplet Bounce-Splash Characteristic: $d = 325\,\mu$, $V_d = 4.6$ ft/sec, $mv = 5.8 \times 10^{-9}\,lb_f$-sec

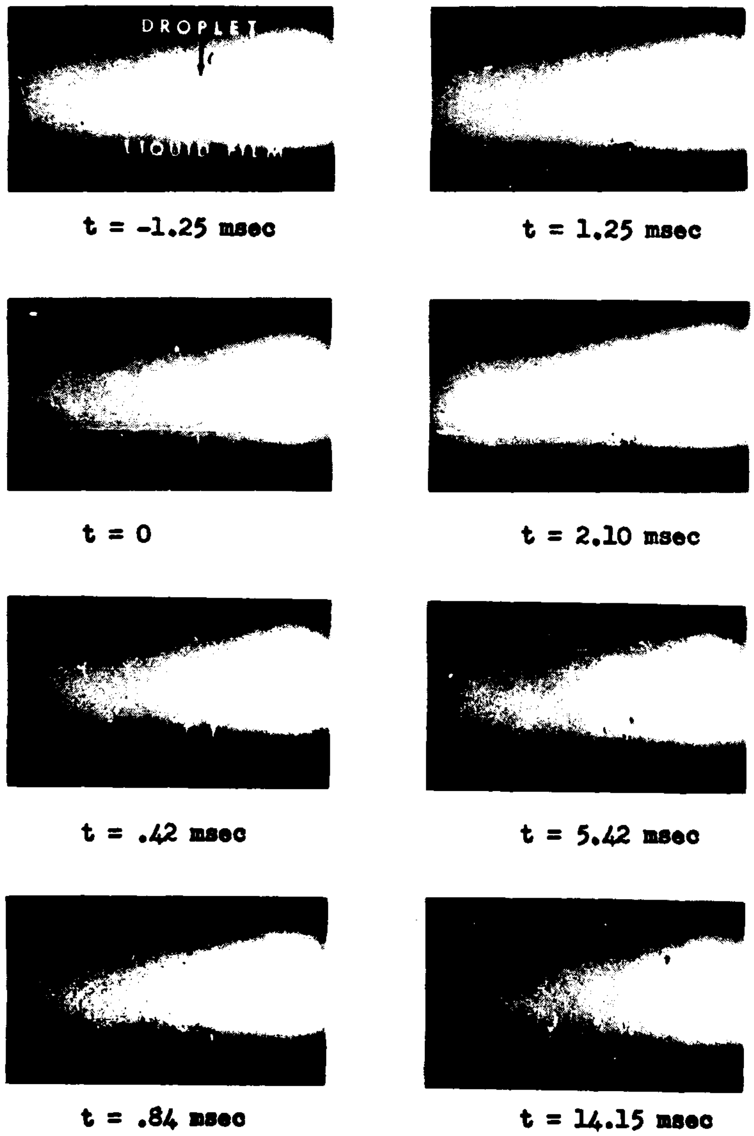
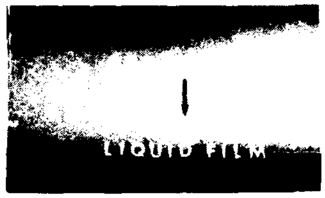


Fig 8 Droplet Splash Characteristic: $d = 350\,\mu$, $V_d = 38.4$ ft/sec, $mv = 61.0 \times 10^{-9} lb_f$-sec

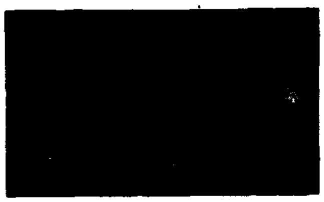
t = -0.19 msec



t = -.15 msec

t = 0.19 msec

t = .90 msec



t = .56 msec

t = 1.64 msec

t = .75 msec

t = 2.09 msec

Fig 9 Comparison of Splash Characteristic for Two Values of Droplet Momentum:
Droplet 1, $d = 225\,\mu$, $V_d = 54.8$ ft/sec, $mv = 20.4 \times 10^{-9} lb_f$-sec;
Droplet 2, $d = 500\,\mu$, $V_d = 37.7$ ft/sec, $mv = 168 \times 10^{-9} lb_f$-sec

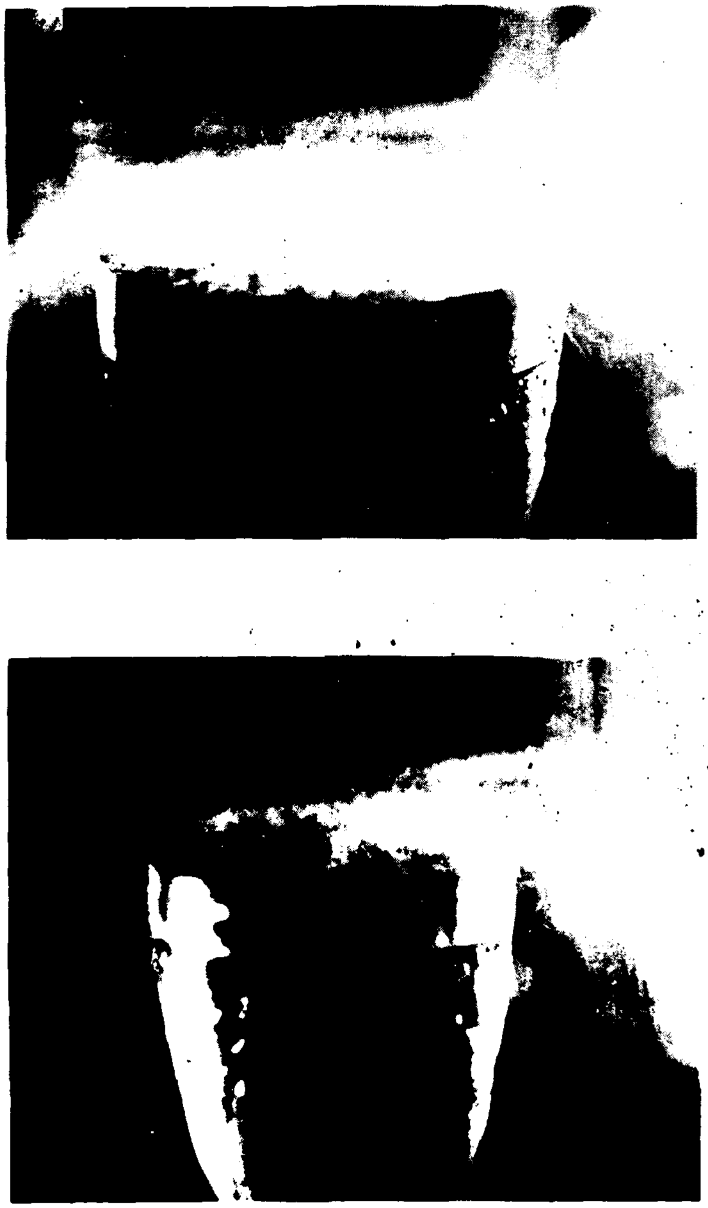


Fig 10 Photographs of the "Halo Effect"

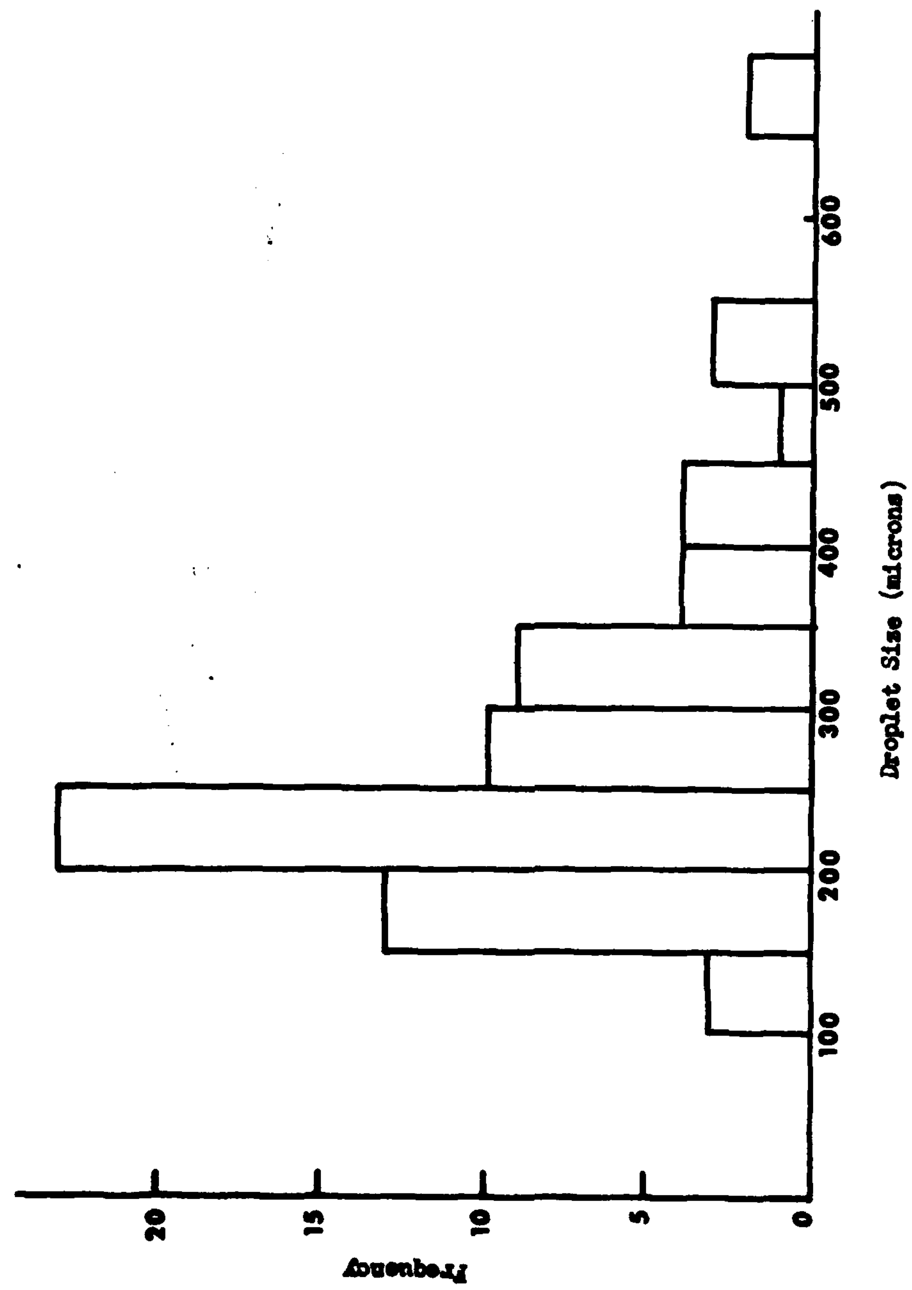


Fig 11 Droplet Size Distribution, Air Velocity = 52 ft/sec

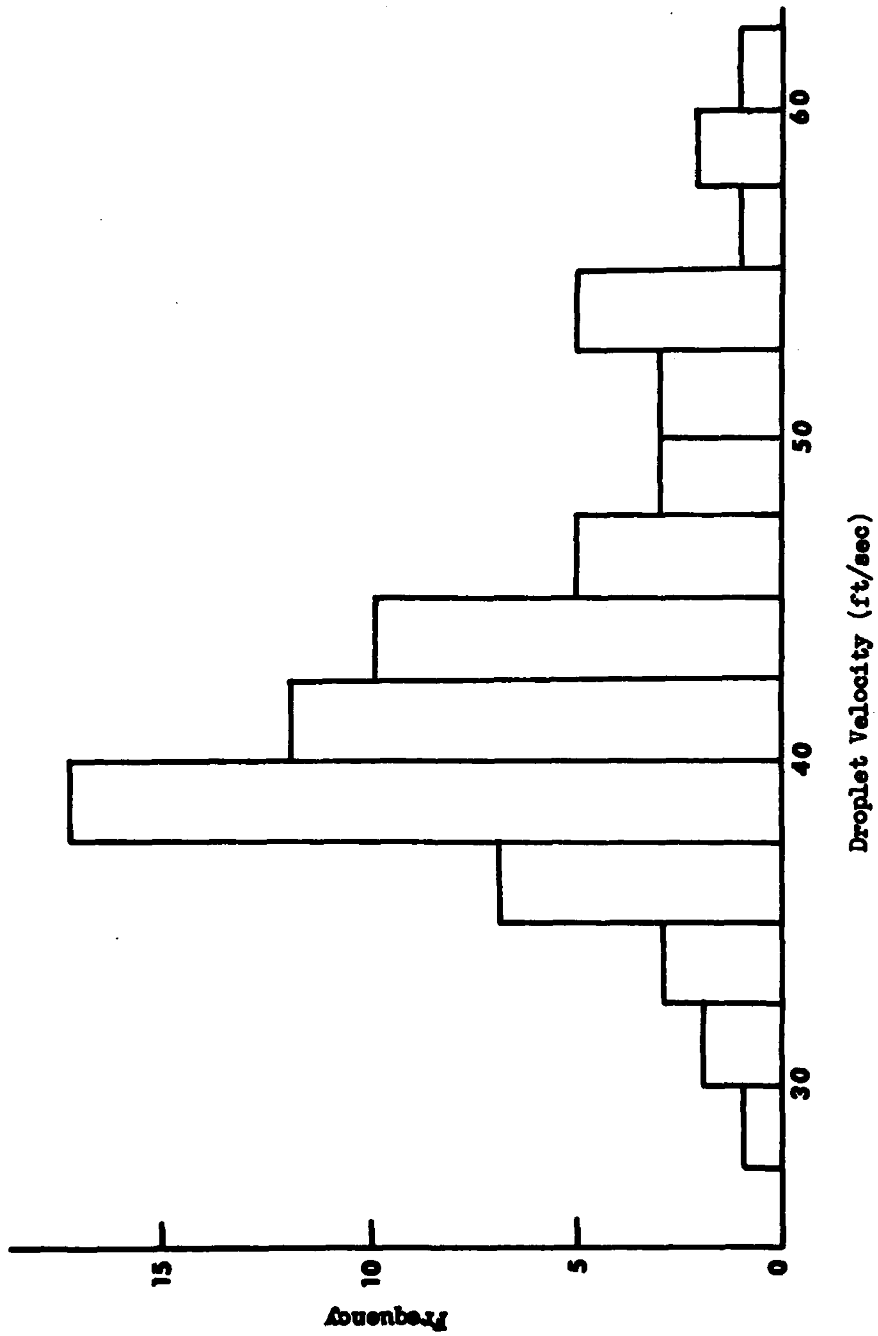
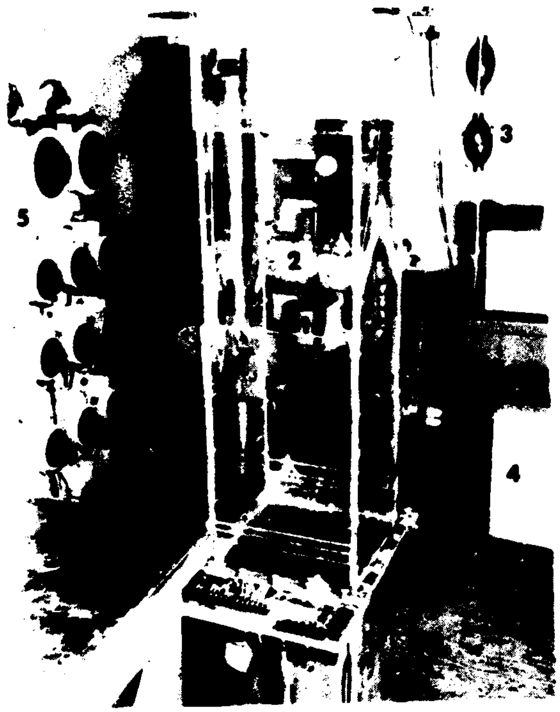


Fig 12 Droplet Velocity Distribution, Air Velocity = 52 ft/sec



1 Flat Plate

2 Fastax Camera

3 Dye Injection System

4 Electronic Timing Equipment

5 Control Panel

Fig 13 Photograph of Test Apparatus

Appendix C

Tables

TABLE I

RESULTS OF DETERMINATION OF WATER DROPLET SIZE, VELOCITY, MOMENTUM, AND IMPACT CHARACTERISTIC

Air Velocity = 0

Droplet Size (microns)	Droplet Velocity (ft/sec)	Droplet Momentum x 10^9 (lb_f-sec)	Impact Characteristic
125	8.43	0.78	B
150	7.42	0.92	B
150	6.92	0.86	B
175	2.52	0.55	B
200	6.82	1.96	B
200	3.31	0.95	B
200	3.20	0.92	B
200	2.40	0.69	B
200	2.97	0.85	B
200	4.18	1.20	B
200	3.14	0.90	B
200	7.46	2.13	B
200	8.92	2.47	B
200	5.82	1.67	B
225	3.37	1.26	B
250	4.27	2.39	B
250	8.30	4.64	B
250	5.34	2.98	B
250	7.00	3.91	B-S
250	6.62	3.71	B
300	5.94	5.74	B-S
300	11.25	10.90	S
300	3.21	3.11	B
300	3.35	3.25	B
300	3.44	3.33	B
300	3.57	3.46	B
300	7.48	7.24	S
325	6.32	8.05	S
350	21.40	33.90	S
350	3.62	5.73	S
350	5.00	7.92	S
400	3.08	7.05	S
400	23.20	53.10	S
400	8.73	20.00	S
400	9.87	22.50	S
450	21.80	71.70	S
475	5.73	22.20	S
475	7.00	27.20	S

TABLE II

RESULTS OF DETERMINATION OF WATER DROPLET SIZE, VELOCITY, MOMENTUM, AND IMPACT CHARACTERISTIC

Air Velocity = 52 ft per second

Droplet Size (microns)	Droplet Velocity (ft/sec)	Droplet Momentum x 10^9 (lb_f-sec)	Impact Characteristic
125	42.5	3.95	S
125	42.8	3.98	B-S
125	45.6	4.25	S
150	54.9	6.80	S
150	44.3	5.50	S
150	57.3	7.12	S
150	61.2	7.60	S
150	57.7	7.17	S
150	37.4	4.65	S
150	38.6	4.81	S
150	38.7	4.82	S
150	46.1	5.73	S
175	45.4	9.85	S
175	53.7	11.65	S
175	43.7	9.48	S
175	32.0	6.95	S
200	43.3	12.41	S
200	47.8	13.70	S
200	53.6	15.35	S
200	38.6	11.05	S
200	35.5	10.15	S
200	54.5	15.61	S
200	42.8	12.25	S
200	42.3	12.10	S
200	41.2	11.80	S
200	40.7	11.65	S
200	37.5	10.75	S
200	43.7	12.50	S
200	40.7	11.65	S
200	37.2	10.65	S
200	38.6	11.05	S
200	38.3	10.95	S
200	44.6	12.80	S
200	37.4	10.71	S
200	42.7	12.20	S
200	44.3	12.65	S
200	38.6	11.05	S
225	48.4	18.05	S

TABLE II--Continued

Droplet Size (microns)	Droplet Velocity (ft/sec)	Droplet Momentum x 10^9 (lb_f-sec)	Impact Characteristic
225	38.9	14.50	S
225	28.1	10.45	S
250	42.7	23.80	S
250	50.8	28.42	S
250	40.3	23.30	S
250	52.0	29.00	S
250	47.8	25.70	S
250	38.0	21.20	S
250	42.7	23.90	S
250	38.9	31.70	S
275	39.6	30.70	S
275	33.1	26.60	S
300	40.3	39.10	S
300	46.3	44.80	S
300	41.8	40.60	S
300	38.1	37.00	S
300	39.9	38.60	S
300	40.6	39.40	S
300	39.1	37.70	S
300	39.9	38.60	S
325	39.5	50.30	S
350	47.0	74.60	S
350	60.0	94.80	S
350	39.6	62.70	S
350	34.1	54.10	S
400	40.6	92.80	S
400	41.3	94.50	S
400	39.4	90.00	S
400	51.7	118.50	S
450	38.2	125.50	S
500	33.4	149.00	S
500	36.7	163.00	S
500	35.8	159.00	S
650	30.5	317.00	S
650	53.6	559.00	S

TABLE III

RESULTS OF DETERMINATION OF WATER DROPLET SIZE, VELOCITY, MOMENTUM, AND IMPACT CHARACTERISTIC

Air Velocity = 82 ft per second

Droplet Size (microns)	Droplet Velocity (ft/sec)	Droplet Momentum x 10^9 (lb_f-sec)	Impact Characteristic
150	86.0	10.7	S
150	63.2	7.9	S
150	81.5	10.1	S
175	75.7	16.5	S
200	72.2	20.7	S
200	93.7	26.9	S
200	92.5	26.5	S
200	68.2	19.6	S
200	69.0	19.8	S
200	80.1	22.9	S
200	74.6	21.4	S
200	64.3	18.4	S
200	67.1	19.3	S
225	95.3	35.5	S
250	53.3	29.8	S
250	77.5	43.3	S
250	84.9	47.5	S
250	76.0	42.4	S
250	60.4	33.8	S
250	81.3	45.5	S
250	66.3	37.1	S
275	76.3	59.1	S
300	73.6	71.5	S
300	53.6	51.9	S
325	83.2	106.0	S
325	75.5	96.1	S
325	79.5	101.5	S
350	60.7	96.2	S
350	64.0	101.5	S
350	64.3	101.6	S
350	60.7	96.2	S
375	61.0	117.5	S
375	76.2	147.0	S
400	59.4	136.0	S
400	51.4	117.5	S
400	61.0	140.0	S
400	52.7	121.0	S
475	46.4	180.0	S
500	62.6	279.0	S
500	77.3	345.0	S

TABLE IV

RESULTS OF DETERMINATION OF WATER DROPLET SIZE, VELOCITY, MOMENTUM, AND IMPACT CHARACTERISTIC

Air Velocity = 125 ft per second

Droplet Size (microns)	Droplet Velocity (ft/sec)	Droplet Momentum x 10^9 (lb_f-sec)	Impact Characteristic
150	90.0	11.2	S
175	95.6	20.8	S
175	95.4	20.7	S
200	109.5	31.4	S
200	105.0	30.1	S
200	89.9	25.7	S
200	77.8	22.3	S
200	115.4	33.1	S
250	104.0	58.2	S
250	96.0	53.6	S
250	93.7	52.3	S
250	87.6	49.0	S
300	103.0	100.0	S
300	86.5	83.7	S
300	112.0	108.5	S
300	101.3	98.5	S
350	91.2	144.5	S
350	97.3	154.0	S
400	95.7	113.5	S
400	80.8	124.5	S
500	94.2	418.0	S
600	103.0	631.0	S

Appendix D

Droplet Isolation Studies

Appendix D

Droplet Isolation Studies

One of the problems encountered in this study was the development of some means of isolating a single water droplet for study. Two particular devices that were considered and later rejected as not feasible were a drawn-out capillary tube and a microliter syringe.

The capillary tube was heated and drawn out as far as possible and then coated with a commercial wetting agent (Desicote). By forcing water through the tube under pressure, single droplets were obtained. However, the smallest droplet had a diameter in the range of 500 microns which is much larger than the droplets normally obtained from a commercial spray nozzle. For this reason, the capillary tube was rejected.

Using a microliter syringe, it was possible to obtain droplets in the range of 100 microns. However, the problem of injecting these droplets into the wind tunnel so that they would strike the plate within the focal area of the camera was not solved. The microliter syringe would be a practical device to isolate a droplet in a static test situation. However, the nozzle adaptor still appears to be most advantageous, since it allows a distribution of droplet sizes and the manual metering of droplets is eliminated.

Vita

Albert Anthony Gagliardi, Jr. was born in Newport, Rhode Island, on 29 June 1937. He attended grade school in Middletown, Rhode Island, and high school in Newport, Rhode Island. He graduated from the United States Air Force Academy, with a Bachelor of Science, on 3 June 1959. After completing pilot training in July of 1960, he was assigned to Laredo AFB, Texas, as an instructor in Undergraduate Pilot Training. In August 1962, he was reassigned to Randolph AFB, Texas, as an instructor in Pilot Instructor Training, where he remained until his entrance into the Air Force Institute of Technology.

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13. ABSTRACT

The purpose of this study was twofold; to determine experimentally the impact characteristics of a water droplet impinging on a flat plate in two-phase, air water spray flow, and to predict on the basis of known heat transfer phenomena, the effect of the impact characteristic on heat transfer. (U)

The apparatus used consisted of a vertical wind tunnel, spray nozzle, spray nozzle adaptor, flat plate, and pressure measuring equipment. High speed motion picture photography was employed to record the impact characteristics as well as to determine the size and velocity of each droplet. (U)

It was observed that a droplet exhibits either one of three impact characteristics: bounce, bounce-splash, and splash. The particular impact characteristic of a droplet was found to be primarily dependent upon its momentum. A discussion of the predicted effect of the impact characteristics on heat transfer is included in the report. The analysis indicates that heat transfer rates are augmented by all of the observed characteristics, and that higher values of heat transfer may be expected with increasing droplet momentum. (U)

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